The ~150 day quasi-periodicity in interplanetary and solar phenomena during cycle 23

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[1] An intermittent quasi-periodicity of ~150 days in various solar and interplanetary phenomena has been reported in earlier solar cycles. We suggest that variations in the occurrence of solar energetic particle events, interplanetary coronal mass ejections, and geomagnetic storm sudden commencements during solar cycle 23 show evidence of this quasi-periodicity, which is also present in the sunspot number, in particular in the northern solar hemisphere. It is not, however, prominent in the interplanetary magnetic field strength.
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1. Introduction

[2] During the current solar cycle, variations in the level of *energetic* solar activity have occurred that are superposed on the general solar cycle variation. For example, Figure 1a shows the intensity of 19–28 MeV solar protons observed by the WIND spacecraft in 1996–late-2004. Note that in late-1997–late-1999, during the ascending phase of the solar cycle (cf. the monthly sunspot numbers in the northern and southern solar hemispheres in Figures 1d–1e), the proton enhancements are not evenly distributed in time, but tend to occur in clusters (in some cases extending over several solar rotations, such as that in late-1998) separated by intervals during which such events are relatively rare. A similar pattern may be discerned during the declining phase of the cycle, from late 2002 until at least the time of writing. In particular, the intense events in October–November, 2003 were preceded and followed by ~4–5 month intervals without major particle events. Around solar maximum, the frequency of events increases, and a similar pattern is less apparent.

[3] Variations in the level of solar activity are also suggested by the rate of interplanetary coronal mass ejections (ICMEs), the manifestations in the solar wind of coronal mass ejections (CMEs) at the Sun, passing the Earth. Figure 1b shows the number of ICMEs/solar rotation, updated from *Cane and Richardson* [2003]. This rate shows prominent variations on timescales of several months. Even around solar maximum, there are depressions in the ICME rate with durations of one or more rotations that suggest temporary reductions in the CME rate at the Sun.

[4] *Cane and Richardson* [2003] noted that the power spectrum of the ICME rate in 1996–2002 had one prominent peak in the 50–300 day range, at a period of 166 days. This period is similar to that of the "~150- (typically 155-) day periodicity" first recognized during solar cycle 21 in the occurrence of gamma ray flares [*Rieger et al.*, 1984] and subsequently identified in other solar and interplanetary phenomena. These include other flare data sets [*Kile and Cliver*, 1991; *Bai and Sturrock*, 1993, and references therein; *Antalova*, 1994], active region parameters [*Lean and Brueckner*, 1989] including sunspot areas [*Lean*, 1990], the soft X-ray background [*Aschwanden*, 1994], solar proton events [*Bai and Cliver*, 1990; *Cane et al.*, 1998], the interplanetary magnetic field [*Cane et al.*, 1998], and the geomagnetic *Ap* index [*Gonzalez et al.*, 1993]. We refer here to the "~150-day periodicity" but recognize that, like the "~11-year" sunspot cycle, this phenomenon is only quasi-periodic. For example, *Lean* [1990] noted that it only occurred intermittently in sunspot areas for intervals of ~1–3 years duration around the maxima of cycles 12–21, while the exact "period" varied from 130 to 185 days, and often changed significantly during an individual cycle. The origin of the "~150-day periodicity" is unclear, in particular whether it originates near the surface of the Sun [*Bai*, 1987, 1988; *Lou*, 2000], reflects changes in the rate of solar magnetic flux emergence [e.g., *Cane et al.*, 1998] or is a global phenomenon [e.g., *Bai and Sturrock*, 1987; *Wolff*, 1992]. *Bai* [1987] and *Lean* [1990] noted an association with complex active regions containing large sunspots ("superactive regions").

[5] Evidence for a "~150-day periodicity" during cycle 23 has been ambiguous. A similar period (~140 days) was reported by *Dalla et al.* [2001] in solar energetic particle events during 1998–1999, and by *Hill et al.* [2001] (151 days) in anomalous cosmic ray intensities in the outer heliosphere, also during 1998–1999. *Ballester et al.* [2004] identified a 163-day period (nearly identical to that reported in the ICME rate) in the Mount Wilson solar index, which emphasizes strong photospheric magnetic flux, around the maximum of cycle 23. However, *Özgüç et al.* [2002] found no evidence of a "~150-day" period in the flare index up to the end of 2000. In this paper, we consider the relationship between the ~166-day "period" inferred by *Cane and Richardson* [2003] from the occurrence rate of ICMEs, and variations in the intensity of energetic solar particle events, the sunspot number, and interplanetary magnetic field (IMF) strength at 1 AU,

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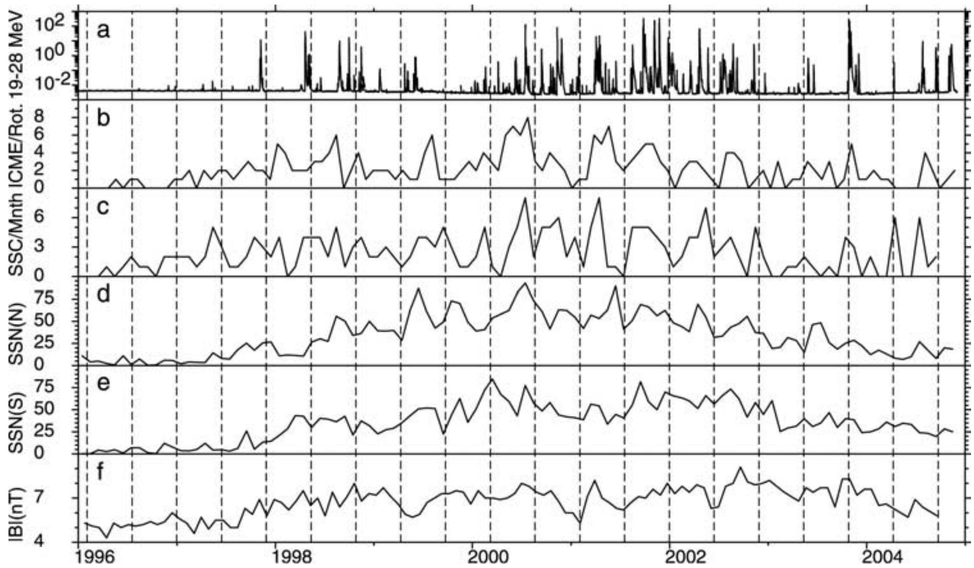

Figure 1. Solar and interplanetary data for 1996–late-2004: (a) WIND/EPACT 19–28 MeV proton intensities (MeV cm^2 sr)$^{-1}$, 8-hour averages); (b) rate of ICMEs/solar rotation, updated from *Cane and Richardson* [2003]; (c) number of SSCs/month; monthly northern (d) and southern hemisphere (e) sunspot numbers; (f) IMF strength (27-day averages). Vertical dashed lines are drawn at 166-day intervals relative to January 1, 2002.

during the ascending, maximum, and descending phases of solar cycle 23.

2. Observations

2.1. Interplanetary Observations

[6] We first examine further the occurrence rate of ICMEs, in Figure 1b. The dashed vertical lines in Figure 1 are drawn (arbitrarily relative to January 1, 2002) at intervals of the 166-day period inferred by *Cane and Richardson* [2003] from the ICME rate in 1996–2002. We suggest that the dashed lines tend to align with the temporary minima in the ICME rate during the ~3-year interval from around mid-1999 to late 2002, encompassing the cycle maximum. Outside this interval, the relationship is less clear. Thus, the "166-day period" inferred in the ICME rate appears to be related to the variations around solar maximum.

[7] Wavelet analysis [e.g., *Torrence and Compo*, 1998] provides a method of examining "quasi-periodic" features in the ICME rate and other data sets in Figure 1, in particular their variation in time. Figure 2 shows wavelet power spectra obtained using a Morelet wavelet with dimensionless frequency $\omega_o = 12$ [cf. *Torrence and Compo*, 1998] which gives reasonable spectral and temporal resolution. The power level scales are arbitrary and linear, and power at periods of 50–300 days is shown. Edge effects may be present in the "cone of influence" indicated by

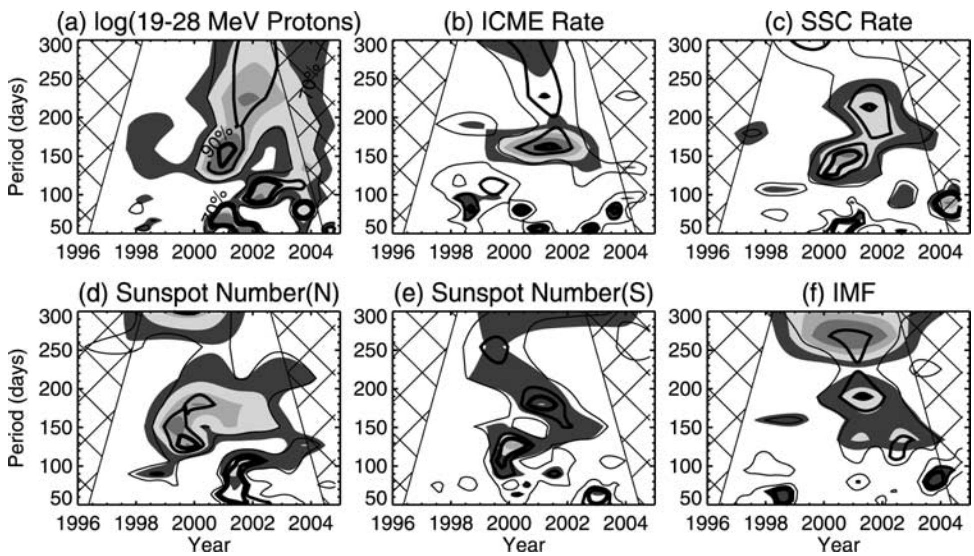

Figure 2. Wavelet analyses for the parameters in Figure 1, in the range 50–300 days. See color version of this figure in the HTML.

hatched areas. Regions with significance levels of 70%, 90% and 95% are indicated by increasingly thicker overlaid contours and assume a red-noise background spectrum (for details, see *Torrence and Compo* [1998]). Figure 2b shows that greatest power in the ICME rate occurred in an "island" of enhanced power centered at ~160 days and extending from ~140 to 180 days, during ~1999 to 2002. This is consistent with the 166-day "period" indicated by the power spectral analysis, and the above conclusions based on inspection of Figure 1b.

[8] We now consider the 19–28 MeV proton intensity. Inspection of Figure 1a suggests that the clusters of energetic proton events during the ascending and descending phases of the solar cycle discussed in the Introduction (including the October–November, 2003 activity) tend to be organized around the vertical dashed lines, suggesting that these are not randomly distributed in time, but have a quasi-periodic component similar to ~166 days. We should emphasize that these proton data are dominated by solar events. At lower energies, this pattern is less conspicuous because interplanetary processes (including particle acceleration at corotating and ICME shocks) contribute more prominently. Wavelet analysis of log(19–28 MeV proton intensity) (Figure 2a) shows maximum power centered on ~150 days in 2000–2001. Evidence for this can be seen in Figure 1a where the larger particle events tend to occur between the vertical lines in 2000–2001. In late 2001–2002, the period of peak power shifts to ~220 days, associated with the multiple particle events during this time. Intermittent signals at periods of ~2, 3 and 4 solar rotations are also present in Figure 2a, associated with activity that persists for several solar rotations. Thus, despite the complexity of the 19–28 MeV proton data around solar maximum, a "~150 day" component was present, at least temporarily. Figure 2a also shows a weak component centered on ~150 days in late-1997–early 1998, consistent with the clustering noted in the introduction, and the *Dalla et al.* [2001] result. The results for late 2003–2004 are compromised by edge effects, though there is an indication of a weak power enhancement at ~135 days that may be related to the event clustering during this period, including the October–November, 2003 activity, discussed above.

[9] Figure 1c shows that variations in the rate(/month) of geomagnetic storm sudden commencements (SSCs; data from the National Geophysical Data Center) usually associated with the Earth passage of interplanetary shocks driven by ICMEs (and less frequently with corotating shocks) are somewhat similar to those in the ICME rate. In particular, minima in the SSC rate also tend to line up with the dashed lines in ~mid-1999–late 2002. Wavelet analysis (Figure 2c) shows an "island" of enhanced power, with maximum power at ~150 days in 2000–mid-2001. As for the proton data, the signal weakens and shifts to longer periods in late 2001. Although affected by edge effects, data for 2004 indicate a strong signal at ~90 days which is also evident in the time series in Figure 1c. In summary, the dominant spectral features in the energetic proton, ICME and SSC data occur around solar maximum and have periods consistent with those of the "~150 day periodicity".

[10] In cycle 21, ~150 day variations were observed in both the interplanetary magnetic field strength and the occurrence of energetic particle events [*Cane et al.*, 1998]. In particular, enhancements in the IMF were associated with increased energetic particle intensities, most conspicuously during the declining phase of the cycle. Figure 1f shows 27-day averages of the interplanetary magnetic field strength at 1 AU (from the NSSDC OMNI database). Overall, variations in the IMF strength during the current cycle are not closely related to those in the ICME rate or SEP intensity, or ordered by the vertical lines separated at 166 day intervals, although we note that the distinct local minima in the IMF in mid-1999, early 2001 and mid-2002 are coincident with temporarily low ICME rates. Wavelet analysis of the IMF strength (Figure 2f) indicates that longer periods, centered around ~270 days which have no counterpart in the proton intensity or ICME rate, are dominant. Power is less strongly enhanced at periods associated with the "150-day periodicity", although there is evidence of intermittent weak signals in this range.

2.2. Solar Observations

[11] We now briefly compare the variations observed in these interplanetary phenomena with those at the Sun, specifically in the monthly sunspot number (SSN) in the northern (SSN(N)) and southern (SSN(S)) solar hemispheres (Figures 1d–1e). Variations in SSN(N) tend to follow to those in the ICME rate and energetic proton intensity (though with occasional exceptions) and show some organization relative to the vertical dashed lines (e.g., the lines tend to align with local minima in SSN(N) around solar maximum, again with exceptions). Wavelet analysis for SSN(N) shows an island of enhanced power in the ~120–200 day range in ~late-1998 to 2002, with maximum power at ~150 days in 1999, increasing to ~170 days in 2000. Weaker signals centered on ~170 days are present until ~2002. Interestingly, SSN(S) (Figure 2e; contours are at the same levels as for SSN(N)) shows much weaker signals than SSN(N) in the ~100–200 day range, with few features consistent with a "150-day" periodicity other than possibly a peak at ~130 days in late-1999–early 2000. Consistent with this conclusion, SSN(S) shows little organization by the vertical lines in Figure 1. A northern-hemisphere bias in the "~150-day periodicity", as suggested by these observations, was also reported by *Lean* [1990] in sunspot areas during cycles 15–21.

[12] We have examined the heliolatitudes of the sources of all >20 MeV solar proton events during this cycle (extending Table 1 of *Cane et al.* [2002]) to see if this bias is reflected in the particle events. We find that northern SEP events outnumber southern, by 3.1:1, in 1999–2000. However, southern events then dominate in 2001–2002 (ratio 0.6:1), giving a ratio of 1.1:1 for the entire 1999–2002 period. The stronger "150-day" periodicity in the proton intensity in 2000, when a similar "periodicity" was still evident in SSN(N) (see Figures 2a and 2d) and northern hemisphere particle events dominated, and weaker periodicity in 2002, when southern particle events were predominant, might be consistent with the northern bias in the SSN periodicity. However, we note that there were few particle events in 1999 (and hence no clear "periodicity" is evident) when peak power at ~150 days occurred in SSN(N). Furthermore, it is evident from Figure 2 that peak power at "~150 days" in the sunspot numbers occurred over a

year earlier than in the energetic particle data or SSC rate, and nearly 2 years earlier than in the ICME rate. Hence, the "150-day" periodicity was not most conspicuous during the same intervals (and at exactly the same periods) in each of the data sets considered here.

3. Summary and Discussion

[13] Inspection of variations in time-series data, and wavelet analysis, suggests that the "∼150-day (quasi)-periodicity" was present in solar and interplanetary activity levels during cycle 23. However, as is typical of such quasi-periodic phenomena, it was only present intermittently, and varied in period, both with time and between the data sets considered. It is manifested most clearly in the wavelet analysis during ∼3 years around solar maximum. At lower activity levels, both during the ascending and descending phase of the cycle, it appears to organize clusters of energetic particle events, including the intense October–November, 2003 events. In the sunspot number, it was more prominent in the northern hemisphere. In contrast to the situation in cycle 21, the "150-day-periodicity" was not present in the IMF strength, which was dominated by longer-period variations.

[14] It has been suggested [e.g., *Bai*, 1989] that identifying patterns of "periodic", or "quasi-periodic" activity in solar and interplanetary phenomena, may provide a tool for solar activity prediction on timescales of several months. However, given the intermittency and variations in period, which also differ between data sets, and the fact that intervals of enhanced activity can persist for several rotations, an accurate (to within a few days) prediction of the onset of future activity is certainly unrealistic. At best, at times when the "periodicity" appears to be is present, a general prediction of possible increased activity ∼150 days (±∼1 − few solar rotations) following a period of energetic solar activity might be made.

[15] **Acknowledgments.** We gratefully acknowledge use of SSC data from the National Geophysical Data Center, sunspot numbers from the SIDC online catalogue (http://sidc.oma.be/html/sunspot.html), and IMF data from the National Space Science Data Center. The WIND/EPACT data were provided via the NSSDC CDAWweb. The wavelet analysis software by *Torrence and Compo* [1998] is available from http://paos.colorado.edu/research/wavelets. IGR is supported by NASA grant NCC 5-180 and HVC by a NASA contract with USRA.

References

Antalova, A. (1994), Periodicities of the LDE-type flare occurrence (1969–1992), *Adv. Space Res.*, *14*(10), 721.

Aschwanden, M. J. (1994), Irradiance observations of the 1–8 Å solar soft X-ray flux from GOES, *Sol. Phys.*, *152*, 53.

Bai, T. (1987), Distribution of flares on the Sun—Superactive regions and active zones of 1980–1985, *Astrophys. J.*, *314*, 795.

Bai, T. (1988), Distribution of flares on the sun during 1955–1985—'Hot spots' (active zones) lasting for 30 years, *Astrophys. J.*, *328*, 860.

Bai, T. (1989), When and where to look to observe major solar flares, in *Max '91 Workshop 2: Developments in Observations and Theory for Solar Cycle 22*, edited by R. M. Winglee and B. R. Dennis, *NASA Tech. Memo., NASA-TM-101893*, 46.

Bai, T., and E. W. Cliver (1990), A 154 day periodicity in the occurrence rate of proton flares, *Astrophys. J.*, *363*, 299.

Bai, T., and P. A. Sturrock (1987), The 152-day periodicity of the solar flare occurrence rate, *Nature*, *327*, 601.

Bai, T., and P. A. Sturrock (1993), Evidence for a fundamental period of the Sun and its relation to the 154 day complex of periodicities, *Astrophys. J.*, *409*, 476.

Ballester, J. L., R. Oliver, and M. Carbonell (2004), Return of the near 160 day periodicity in the photospheric magnetic flux during solar cycle 23, *Astrophys. J. Lett.*, *615*, L173.

Cane, H. V., and I. G. Richardson (2003), Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002, *J. Geophys. Res.*, *108*(A4), 1156, doi:10.1029/2002JA009817.

Cane, H. V., I. G. Richardson, and T. T. von Rosenvinge (1998), Interplanetary magnetic field periodicity of ∼153 days, *Geophys. Res. Lett.*, *25*, 4437.

Cane, H. V., W. C. Erickson, and N. P. Prestage (2002), Solar flares, type III radio bursts, coronal mass ejections, and energetic particles, *J. Geophys. Res.*, *107*(A10), 1315, doi:10.1029/2001JA000320.

Dalla, S., A. Balogh, B. Heber, and C. Lopate (2001), Further indications of a ∼140 day recurrence in energetic particle fluxes at 1 and 5 AU from the Sun, *J. Geophys. Res.*, *106*, 5721.

Gonzalez, A. L. C., W. D. Gonzalez, S. L. G. Dutra, and B. T. Tsurutani (1993), Periodic variation in the geomagnetic activity: A study based on the *Ap* index, *J. Geophys. Res.*, *98*, 9215.

Hill, M. E., D. C. Hamilton, and S. M. Krimigis (2001), Periodicity of 151 days in outer heliosphere anomalous cosmic ray fluxes, *J. Geophys. Res.*, *106*, 8315.

Kile, J. N., and E. W. Cliver (1991), A search for the 154 day periodicity in the occurrence rate of solar flares using Ottawa 2.8 GHz burst data, 1955–1990, *Astrophys. J.*, *370*, 442.

Lean, J. L. (1990), Evolution of the 155 day periodicity in sunspot areas during solar cycles 12 to 21, *Astrophys. J.*, *363*, 718.

Lean, J. L., and G. E. Brueckner (1989), Intermediate-term solar periodicities: 100–500 days, *Astrophys. J.*, *337*, 568.

Lou, Y.-Q. (2000), Rossby-type wave-induced periodicities in flare activities and sunspot areas or groups during solar maxima, *Astrophys. J.*, *540*, 1102.

Özgüç, A., T. Ataç, and J. Rybák (2002), Flare index variability in the ascending branch of solar cycle 23, *J. Geophys. Res.*, *107*(A7), 1146, doi:10.1029/2001JA009080.

Rieger, E., G. H. Share, D. J. Forrest, G. Kanbach, C. Reppin, and E. L. Chupp (1984), A 154-day periodicity in the occurrence of hard solar flares?, *Nature*, *312*, 623.

Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61.

Wolff, C. L. (1992), 'Intermittent' solar periodicities, *Sol. Phys.*, *142*, 187.

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